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ARTICLE

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WIND ENERGY HARVESTING PROGRAM OF CSIR–NAL: A SAGA OF AEROSPACE SPIN-OFF FOR SOCIETAL BENEFIT AND SUSTAINABILITY

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As an aerospace spin-off, Council of Scientific and Industrial Research-National Aerospace Laboratories (CSIR-NAL) has been actively fostering swadeshi technologies for harvesting wind energy since its inception. CSIR-NAL has played a pivotal role in realizing the first wind map of India, developing different kinds of off-grid and on-grid wind turbine designs for water pumping and energy generation, and hybridizing them with other renewable energy sources. The present article is a technical narration of this adventurous journey of CSIR-NAL in the past decades.

Keywords: *COP-28, climate change, carbon footprint, wind turbine, wind-solar hybrid, sustainability, spin-off*

Introduction

At present, there is a strong international impetus on sustainability and harvesting renewable energy to combat climatic change and reduce carbon footprint. Conference of the Parties (COP)–28, the United Nations (UN) event in Dubai from 30th November to 12th December 2023, laid special emphasis on phasing out fossil fuel usage and adopting renewable energy. An appeal was made to all the nations to triple renewable energy capacity and double energy efficiency improvements by 2030[1]. At national level, India has made a strong commitment to these efforts by targeting 500 GW of energy generation from non-conventional renewable energy sources by 2030[2]. As per the wind resource assessment studies of the National Institute of Wind Energy (NIWE), the wind power potential at 120 m above ground level (AGL) is about 695.5 GW and at 150 m AGL is about 1,164 GW [3]. This implies that wind energy alone can achieve the ambitious target of 500 GW of renewable energy installations. However, as against the available potential, the present installed capacity of wind energy in India is 47.363 GW as of 30th September, 2024[4]. This huge gap between the available potential and exploited potential of wind energy can be reduced by putting special emphasis on developing wind turbine technologies customized to optimally operate and generate electricity in sub-tropical climatic conditions prevailing in Indian peninsular terrain. It is a surprising fact that CSIR–NAL had far-sighted wisdom about the ill effects of climate change and the need for reduction in greenhouse gas emissions by harvesting wind energy during the days of its inception. Realizing the dire need to harvest wind energy, CSIR–NAL had initiated research and development of wind energy technologies since its establishment alongside its efforts in developing core aerospace technologies. CSIR–NAL is the only engineering lab of the CSIR, an autonomous body under the Department of Science and Technologies (DST), Government of India, whose primary focus is on aerospace research in India. CSIR–NAL is mandated to evolve aerospace technologies with strong science content, design and build small and medium-sized civil aircraft and support all national aerospace programs. Not confined to only aerospace

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technologies, CSIR–NAL has also realized spin-off derivatives from the in-house aerospace knowledge base for societal and strategic sectors. Wind energy harvesting technologies are one of such spin-offs of CSIR–NAL for the societal sector. The next part of this article narrates the historical saga of how CSIR–NAL contributed to the vision of the Government of India to harvest wind energy by developing India-centric wind energy harnessing technologies from its time of establishment till the present time.

The Incubation Phase (Pre 1959 Period)

Seeds of wind energy harvesting were sown in the minds of Dr. P. Nilkantan, the first Director of CSIR–NAL, much before the inception of CSIR–NAL. After the manifestation of India as an independent republic in 1950, the then far-sighted leaders of India were well-vigilant about attaining energy independence by harvesting renewable energy. With a vision to harvest the untapped wind energy resources of India, CSIR set up a Wind Power Sub-Committee in December 1952 under the leadership of Prof. M. S. Thacker and Dr. P. Nilakantan as the Investigator-In-Charge[5]. This committee carried out preliminary studies on the wind potential available in the Indian sub-continent which could be commercially exploited. It took a database available from the Indian Meteorological Department (IMD) and started identifying the windy pockets for wind energy harvesting. After a few years of studies, the committee concluded that there existed large untapped high wind locations where wind power could profitably be utilized for potable water pumping, sanitation, irrigation of small holdings, drainages, processing of agricultural products like grinding corn, threshing, and oil extraction. Subsequently, the committee proposed to carry out a detailed wind resource assessment of the candidate windy sites and initiate developmental work on wind turbines in the range of 6–8 kW capacity. In September 1954, when a Symposium on Solar Energy and Wind power was jointly organized by the United Nations Education, Scientific, and Cultural Organization (UNESCO) and CSIR, Mr. E. W. Golding of the British Electrical and Allied Industries Association, United Kingdom visited India[6]. During his tour, he went across India and surveyed areas that had potential for wind energy generation. Recognizing the immense potential to tap wind energy in India, he recommended that a dedicated team of scientists should work on theoretical and experimental studies of wind turbine technology by establishing research labs, test facilities, and field research stations. The Board of Scientific and Industrial Research accepted these recommendations during the Governing Body meeting of CSIR in 1957[6]. CSIR–NAL was born on 1st June 1959 in Delhi and was shifted to Bengaluru in 1960. It was at this time that a dedicated Wind Power Division was formed as a part of CSIR–NAL. The mandate of the division was to develop indigenous wind power generation technologies as an aerospace spin-off.

The Ascending and Descending Phase (Period between 1959 to 1975)

This was the phase where CSIR–NAL focused on studying the existing windmill and then designing, developing, demonstrating, and carrying out the performance studies of the indigenous windmill, Wind Pumper (WP). WP windmill was a metallic multi-bladed system with a tower top drive train supported by a ball-bearing turn-table, a reciprocating water pump, a passive furling mechanism to disorient the rotor beyond 30 miles per hour wind speeds, and a site-specific 4-post tower with height varying from 30 to 50 feet. WP windmill had two variants, WP-1 and WP-2. The primary difference between these two variants was that WP-1 had a geared drive train and WP-2 was a direct drive system. Fig. 1[7,8] shows WP-1 and WP-2 under field verification and validation along with other imported windmills at a dedicated field test station at Kodihalli campus, CSIR–NAL, Bengaluru.

During the Governing Body meeting of CSIR on 25th March 1961, approval was accorded for a project to install and maintain 200 nos. of WP-2 windmills developed by CSIR–NAL across India. To support this program, an Installation and Maintenance Unit was formed at CSIR–NAL. The tower top drive-train sub-system was manufactured by Bharat National Foundry, Delhi. Towers,

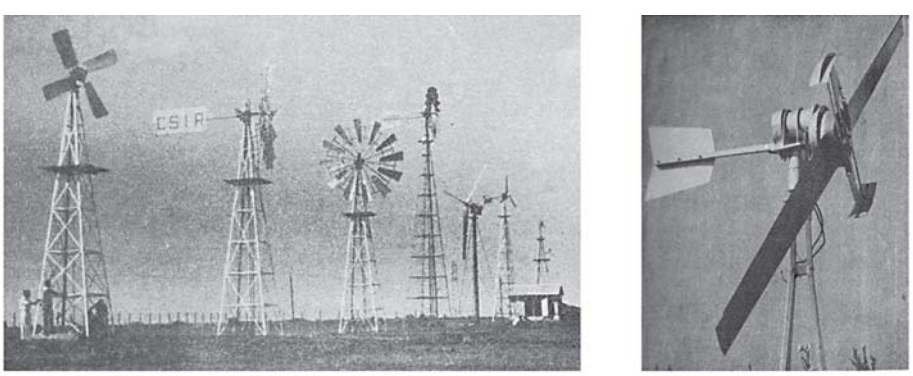


Fig. 1: Different windmills under testing at CSIR–NAL field test station, Kodihalli.

rotors, and tail-vanes were fabricated by Tungabhadra Steel Products Ltd., Hospet. Windmills were installed across India at Leh, Ladakh, and other border areas, New Delhi, Rajasthan, Maharashtra, Tamil Nadu, and Karnataka with the help of local governing authorities. A WP-2 system was gifted to the Imperial Ethiopian College of Agriculture and Mechanical Arts, Addis Ababa, Ethiopia, East Africa in October 1964. Following the commissioning of WP-2 windmills, their performance and operational issues were studied, and necessary design changes were devised and implemented. Better and more robust prototypes were then manufactured and tested. Fig. 2[9] shows the load testing of a reinforced WP-2 windmill rotor being carried out at CSIR–NAL.

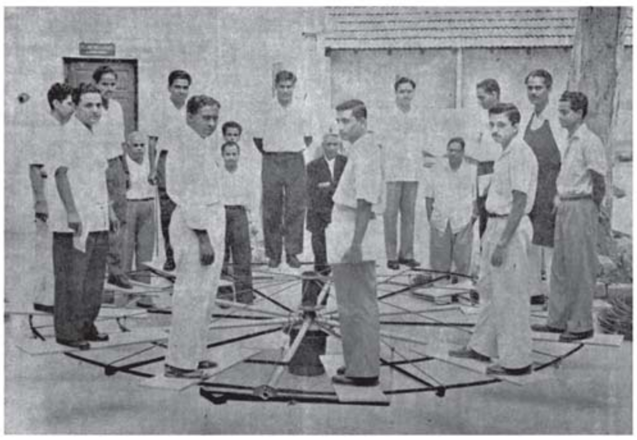


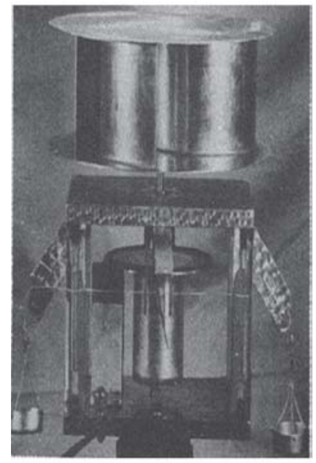
Fig. 2: Reinforced rotor of WP-2 windmill undergoing load testing at CSIR–NAL.

The indigenous wind turbine developmental activities for water pumping and battery charging applications were accompanied by study of the wind measurement database published by the Indian Meteorological Department (IMD). While these activities continued till the untimely demise of Dr. P. Nilakantan in 1964, further wind turbine development activities remained suspended from 1965 to 1974.

Rise of Vertical Axis Wind Turbines, Sail Wind Mill, and First Wind Map of India (Period between 1975 to 1985)

The oil crisis began in October 1973, when the members of the Organization of Arab Petroleum Exporting countries declared an oil embargo on nations that supported Israel during the Yom Kippur Wars. This resulted in a renewed interest in wind power generation. CSIR–NAL, which was marching towards developing indigenous civil aircraft, could not remain untouched from this "wind rush". Windmill development activities again rekindled at CSIR–NAL in 1975. Apart from research on horizontal axis wind turbines, this phase witnessed the development of vertical axis wind turbine designs (Fig. 3a and 3b)[10] at CSIR–NAL.

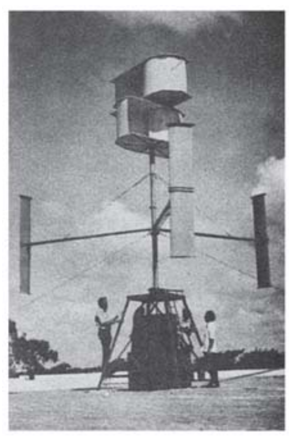
(a) Darrieus windmill.



(b) Wind tunnel testing of Savonius windmill.

Fig. 3: Vertical axis windmills developed by CSIR–NAL.

Prototypes of 1 kW straight-bladed VAWT (Fig. 4a)[11] and 10 m diameter sail-type windmills (Fig. 4b)[12] were designed, developed, and demonstrated at CSIR–NAL.



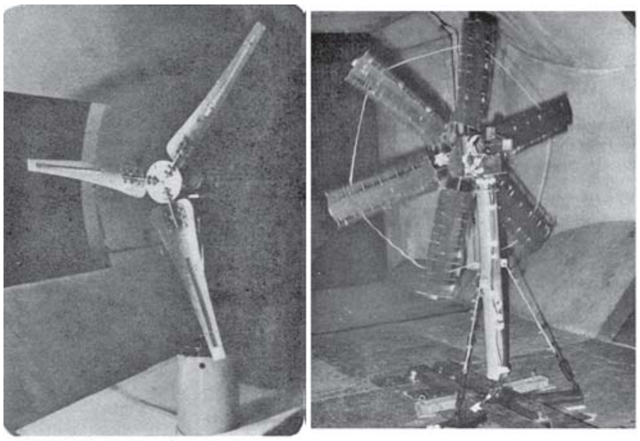
(a) Straight bladed VAWT prototype.

(b) Sail type HAWT prototype.

Fig. 4: Windmills under testing at Kodihalli campus, CSIR–NAL.

Constant endeavours were made to perfect the mechanical components like the rotor, transmission shaft, gearbox, pumps, and sail mounting shafts to withstand the harsh outdoor operating conditions. Apart from the sail-type windmills, a prototype battery-charging wind turbine was also designed, developed, and experimented in 0.9 m wind tunnel of CSIR–NAL (Fig. 5a)[13]. Innovative approaches for over-speed control of the sail-type rotors were evaluated at Low-Speed Wind Tunnel Facilities of Indian Institute of Science (IISc), Bengaluru (Fig. 5b)[14]. These research activities revealed that even during the

1970s and 1980s period, when resources were limited, CSIR–NAL resorted to sophisticated wind tunnel techniques to fine-tune the in-house windmill blade shapes that would optimally convert kinetic energy of wind into mechanical or electrical power.



(a) Wind turbine testing at CSIR–NAL.

(b) Sail-type windmill testing at IISc.

Fig. 5: Windmills undergoing wind tunnel testing.

Apart from windmill development activities, CSIR–NAL also continued to carry out wind studies across India during this decade. Wind data from IMD was studied and wind energy maps in terms of $kWh/m^2/day$ were developed by scientists of CSIR–NAL (Fig. 6)[14]. This was the pioneering work in the country from the viewpoint of harnessing wind energy in India. Later, many other government agencies and private entities followed the footsteps of CSIR–NAL. This fact has been acknowledged by National Institute of Wind Energy (formally known as Centre for Wind Energy Technology), an autonomous body under the Ministry of New and Renewable Energy, Government of India and the nodal agency for wind energy in India, in their publication Indian Wind Power Atlas.

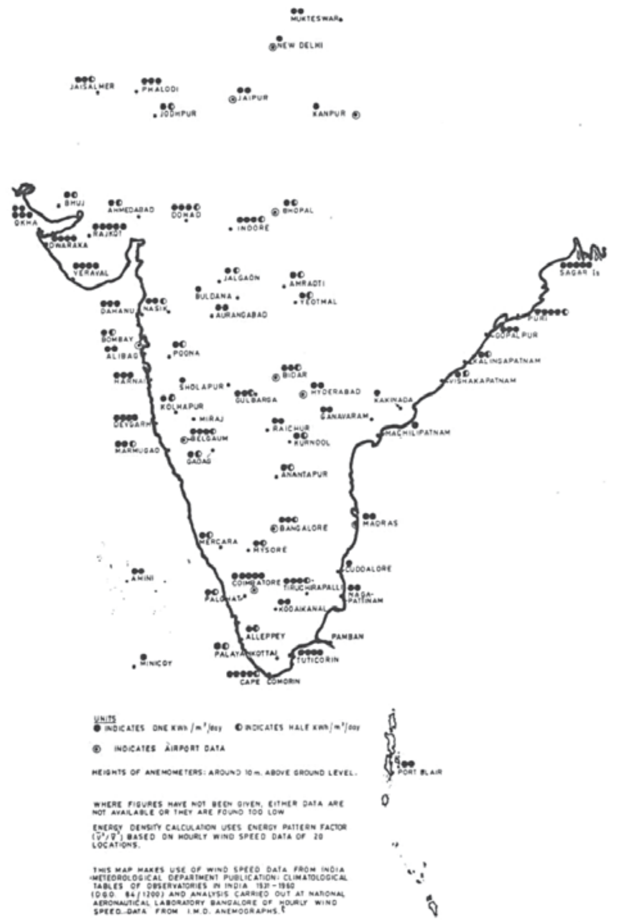
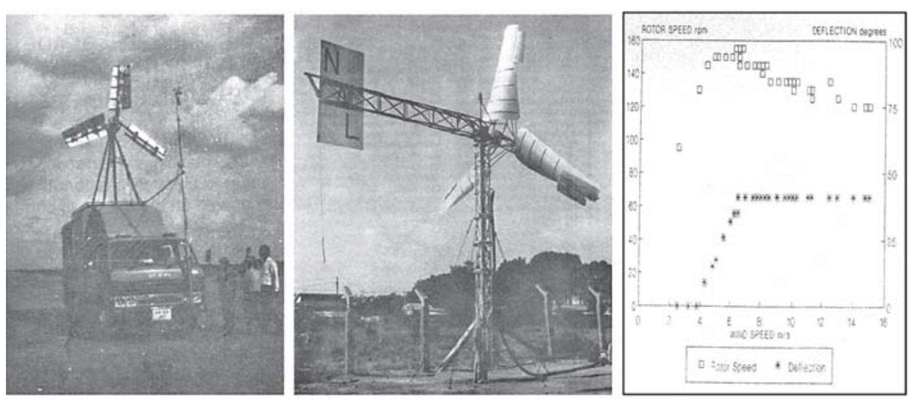


Fig. 6: Wind Power Map of India published by CSIR–NAL.

Birth of Samira Wind Mill, Numerical Simulations and Wind Resource Assessment (Period between 1985 to 1995)

Field trials of the sail-type windmills during the early 1980s demonstrated that robust windmill designs were required for water-pumping applications and power generation applications. This paved the way for the design, development, fine-tuning, and field trials of metallic Samira windmills. Many of the learnings of sail-type windmills helped to develop the Samira windmill. While key features of overspeed protection and overall support structure configurations were retained, new features for improving the performance of rotor blades, like leading edge slats, were incorporated. Tow testing (Fig. 7a)[15], i.e., performance evaluation of an instrumented scale-



(a) (b) (c)

Fig. 7: Samira undergoing testing: tow testing and (b) field trials at CSIR–NAL and (c) experimental power curve.

down prototype of the system over a mobile test vehicle, and field trials at the wind farm of CSIR–NAL (Fig. 7b)[16] were carried out to fine-tune the system.

Having carried out the tow-testing and the field trials of Samira, a prototype was installed at Salt Farm in Tuticorin as a technology demonstrator in collaboration with Southern Petrochemicals Industries Corporation. Extensive field trials were carried out to perfect the different sub-systems of Samira to work optimally in harsh coastal environmental conditions. During these trials, it was reported that Samira had to potential to reduce 5 – 6 litre of diesel usage per day. Having successfully perfected the robustness of Samira, a national demonstration program was sponsored to CSIR–NAL by the Department of New Energy Sources. Under this flagship program, 9 Samira windmills were installed by the licensee of CSIR–NAL in Andhra Pradesh, and 5 machines were proposed to be installed in Odisha.

While on one hand, the experimental approaches were adopted to fine-tune the systems, a team of researchers at Wind Energy Group, CSIR–NAL explored the numerical approach to study the flow physics of the novel aerodynamic devices of the windmill blades and structural integrity of the windmill towers. Fully viscous numerical simulation studies of slatted NASA LS(1) 0417 airfoil were carried out using vortex dynamics modeling, and an optimal slat configuration which would ensure overspeed protection of the windmill rotor in high wind conditions was ascertained (Fig. 8)[17]. Dynamic analysis of the metallic blade, free-standing lattice tower, and the entire Samira wind turbine assembly was carried out using FEMGEN pre-processor and Automatic System of Kinematic Analysis (ASKA) Finite Element (FE) code (Fig. 9)[18].

Fig. 8: Numerical simulation.

Another research vertical of wind energy harvesting, which is the prelude for setting up a wind farm, is Wind Resource Assessment (WRA). Realizing the long-term benefit of research in WRA, the Wind Energy Group of

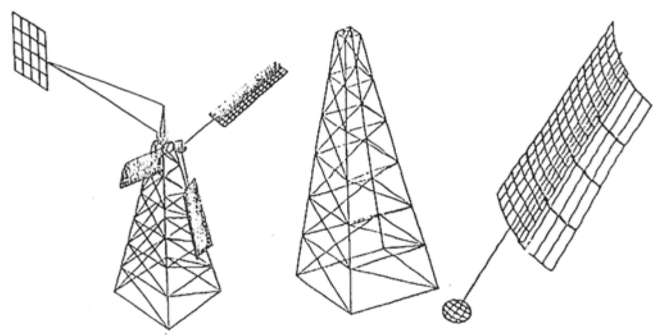


Fig. 9: Finite Element simulation.

CSIR–NAL initiated preliminary work on this aspect. While today's Light Detection and Ranging (LiDAR) equipment measures the meteorological parameters at heights above 100 meters, conducting a trivial-looking measurement of wind speed and wind direction at a height of even 30 m was a technological challenge during the 1980s in India. For this purpose, an in-house met-mast design was developed and WRA activities were taken up in 6 states of India in collaboration with different government and defense organizations like Snow and Avalanche Study Establishment (SASE) – Defence Research Development Organization (DRDO), Karnataka State Industrial and Infrastructure Development Corporation Limited (KSIIDC), Karnataka Power Corporation Limited (KPCL), Indian Institute of Tropical Meteorology (IITM), and Department of Science – Government of Manipur. CSIR-NAL carried out WRA at Banihal Pass in Jammu and Kashmir, Bhagamandala, Talacauvery ridges, Gadad, Kappataguda, the stretch spanning from Harpanahalli, Chitradurga and Chikanayakanahalli in Karnataka, Kalingapatnam, Bhimunipatnam, Yeradu, Pollekoru and Tirumala Hills in Eastern Ghat in the then Andhra Pradesh, Jaipur, Phalodi, Jaisalmer, Barmer and salt lake area in Jodhpur in Rajasthan, Aramboli gap near Kanyakumari, Kayattar and Palghat Gap in Tamil Nadu and few locations in North Eastern India. While carrying out the WRA, CSIR–NAL not only created the repository of the wind patterns across India but also created the digital terrain maps of the areas (Fig. 10)[18,19], which exhibited potential for exploiting wind resources. This fact reveals that during the 1990s itself, CSIR–NAL had employed the futuristic digital twin methodology for harvesting wind energy in India.

Mission Antarctica, Wind Flow Modelling training with Risø National Laboratory (Denmark), and Turbine Performance Studies (Period between 1995 – 2002)

CSIR–NAL did not confine its outreach of harvesting wind energy to the Indian sub-continent alone. It played a

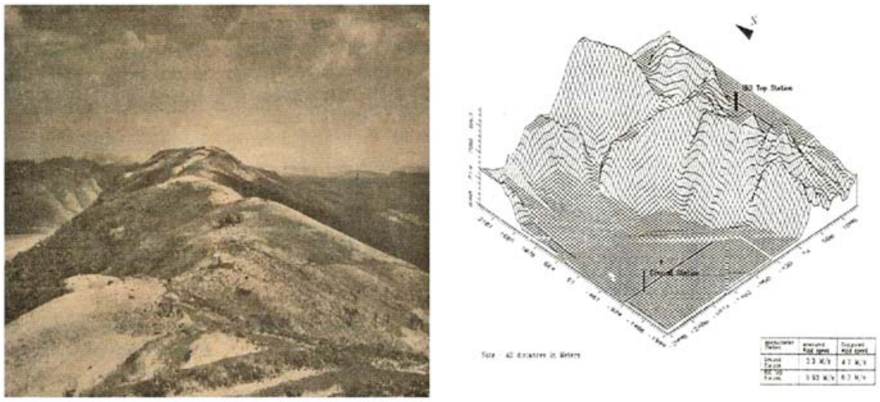


Fig. 10: Part of Kappatagudda Hills and its digital twin created by CSIR–NAL.

crucial role in laying the foundation for harvesting wind energy at *Maitri* – Indian Polar Research Station in Antarctica. The Steering Committee on Antarctic Research set up by the Department of Ocean Development (DOD) under the chairmanship of Prof. U R Rao recommended that alternative sources of energy should be used to supplement the station's own and its field camp's energy requirements. In response to this recommendation, CSIR–NAL submitted a proposal on wind resource assessment and harnessing wind energy at the *Maitri* research station. The proposal was reviewed by expert groups and approved to be implemented during 16th and subsequent Antarctica Missions. Subsequently, CSIR–NAL participated in 16th to 21st Antarctica Missions along with teams from other Government departments. During the 16th Antarctica mission in 1996, a met-mast was installed and commissioned. Wind patterns at three levels viz., 12 m, 22 m, and 28 m AGL were recorded and wind power density (WPD) in areas near *Maitri* research station in Antarctica was experimentally ascertained (Fig. 11)[20,21]. In parallel, a study about the terrain features and energy requirements for electrical equipment and heating at *Maitri* research station were collected to chalk out a strategy to harvest wind energy to cater to these requirements. During the 17th Antarctica mission in 1997, battery-charging wind turbines with 72 W, 12 V ratings were installed at Vittiah peak (Fig. 12)[22] and automotive workshop near *Maitri* research station. During the 18th Antarctica mission in 1998, the key focus was on operation and maintenance of the wind turbines for battery charging and the met-mast. During the 19th Antarctica mission in 1999, few operational issues of the wind turbines for battery charging, that were faced during the high wind conditions, were addressed. A new wind turbine with 340 W 12 V rating and 630 Ah battery bank was installed near Nanda Devi hut in Antarctica.

Fig. 12: Wind battery charger.

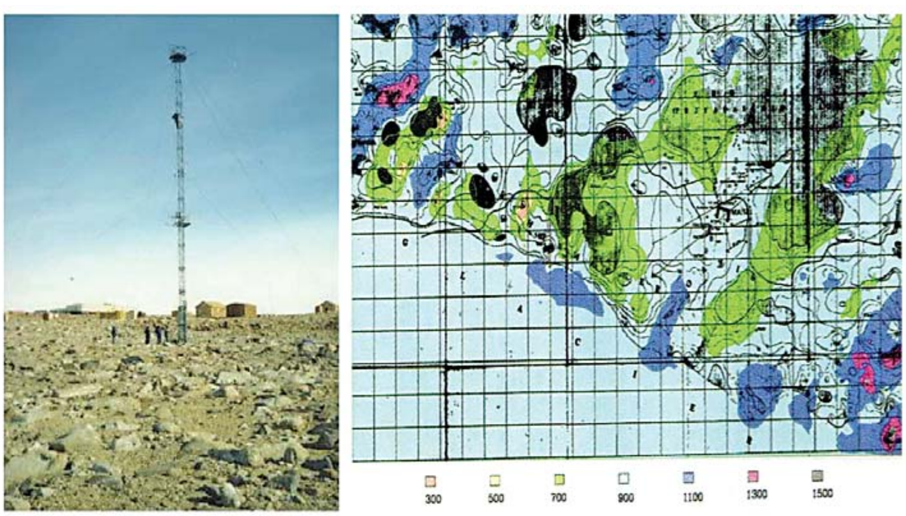


Fig. 11: Met-mast at Antarctica and WPD.

During the 20th Antarctica mission in 2000, indigenously developed Savonious-type vertical axis wind turbine prototypes were installed and their field performances were studied. This apart, installation of a wind turbine for battery charging was carried out over the mobile laboratories to power the instruments used in the field camps. During the 21st Antarctica mission in 2001, two improved variants of the Savonious type vertical axis wind turbines were commissioned at Vittiah Peak and at automotive

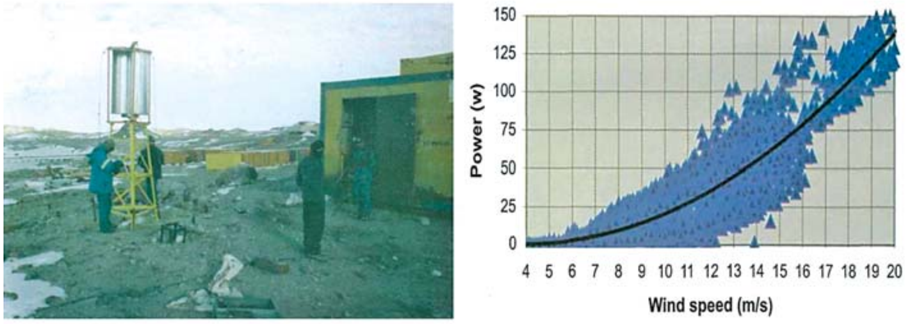


Fig. 13: Savonious Wind Mill at automotive station workshop and its field performance.

Fig. 14: Wind Flow Modelling workshop at CSIR–NAL by Scientist of Risø National Lab.

station workshop in Antarctica to power the repeater station (Fig. 13)[23]. The field evaluation of these systems were continued till 2002.

While spreading its fame in Antarctica, CSIR–NAL was also vigilant about harvesting wind energy in India. With the vast in-house wealth of WRA and the digital terrain map, that were created in the past decade, CSIR–NAL collaborated with the acknowledged global experts in Wind Energy and laid the foundation of wind flow modeling in India. The first workshop of its kind was organized at CSIR–NAL from 14–17 November 1996 (Fig. 14)[20] in collaboration with Risø National Laboratory, Denmark, and financially supported by the Danish International Development Agency (DANIDA), Ministry of Non-conventional Energy Sources (MNES), Indian Renewable Energy Development Agency (IREDA) and state nodal energy development agencies. The workshop witnessed participation from wind machine manufacturers, wind farm developers, researchers from different research laboratories, and state nodal agency engineers. The workshop witnessed invited lectures, hands-on experience of Wind Atlas Analysis and Application Program (WAsP) – a techno-economic optimization tool, and illustration of the usage of WAsP through practical case studies.

To validate the forecasting of the energy yield from WAsP code, data from the wind farms were needed. Realizing this gap, CSIR–NAL embarked on power curve measurements of different wind farms across India. This was a period when not many private firms ventured into power curve measurement activities. Hence, many private wind farms offered sponsored projects to CSIR–NAL for carrying out power curve measurements. Prominent among them were Jindal Wind Farm (Fig. 15)[24], Goetze Financial Services wind farm near Hiriyur (Fig. 16)[24] and projects at the Sahyadri range of hills off the Arabian Sea in Maharashtra.

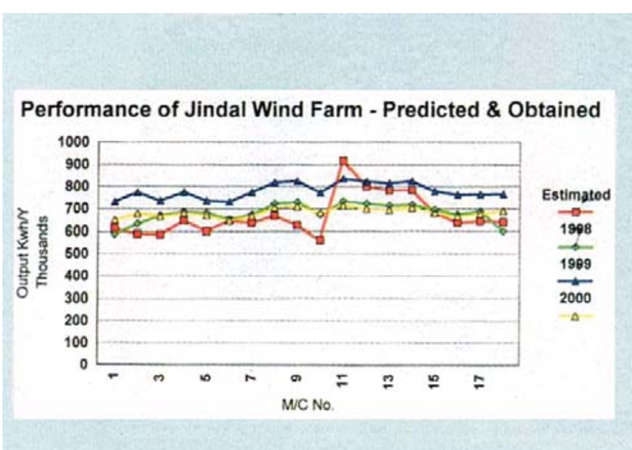


Fig. 15: Performance of Jindal wind farm

Fig. 16: Wind farm at Hiriyur.

These activities helped in the creation of an Indian database of wind patterns as well as wind farm performance. Later, this database was used in designing India-specific wind turbines that would optimally work in Indian low wind conditions.

Rise of Grid-Connected Medium Wind Turbine Systems (Period between 2002 – 2012)

After the Antarctica expedition, CSIR–NAL embarked on designing, developing, and demonstrating India-centric grid-connected wind turbine systems. CSIR–NAL started this new voyage by collaborating with M/s Sangeeth Group of Companies (SGC), Coimbatore. M/s SGC was facing problems in replacing the damaged blades of the Carter 300 kW grid-connected wind turbines as the original equipment manufacturer (OEM) had discontinued the production. With the in-house expertise in Glass Fibre Reinforced Polymer (GFRP) based mega-structures like radomes, CSIR–NAL studied the composite blades and helped in manufacturing, replacing and commissioning of 12.5 m wind turbine blades made of GFRP material (Fig. 17)[25]. Performance of the wind turbines with these indigenous blades were studied and found to be better (Fig.18)[25] than the original blades.

Fig. 17: Installation and commissioning of 300 kW wind turbine.

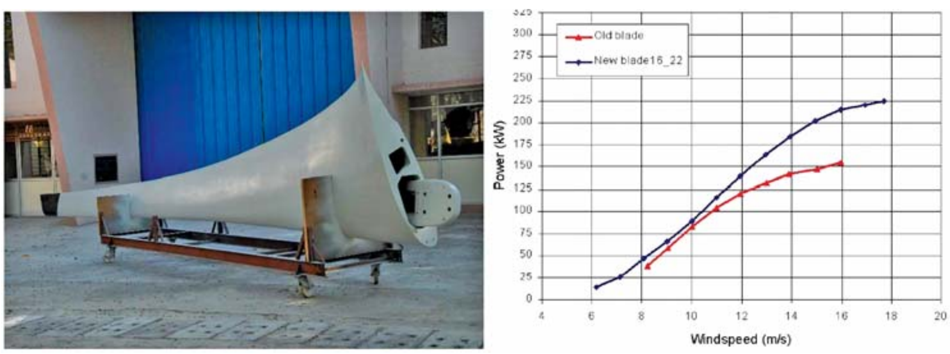


Fig. 18: Indigenously developed 300 kW blade and its field performance studies.

Having gained experience from the 300 kW wind turbine blade development, CSIR–NAL embarked on the design, development, and technology demonstration of a 500 kW wind turbine under CSIR's New Millennium Indian Technology Leadership Initiative (NMITLI) flagship program. This was a multi-lab program and was executed with help from CSIR – Structural Engineering Research Centre (SERC), our sister lab at Chennai, Tamil Nadu, and in collaboration with

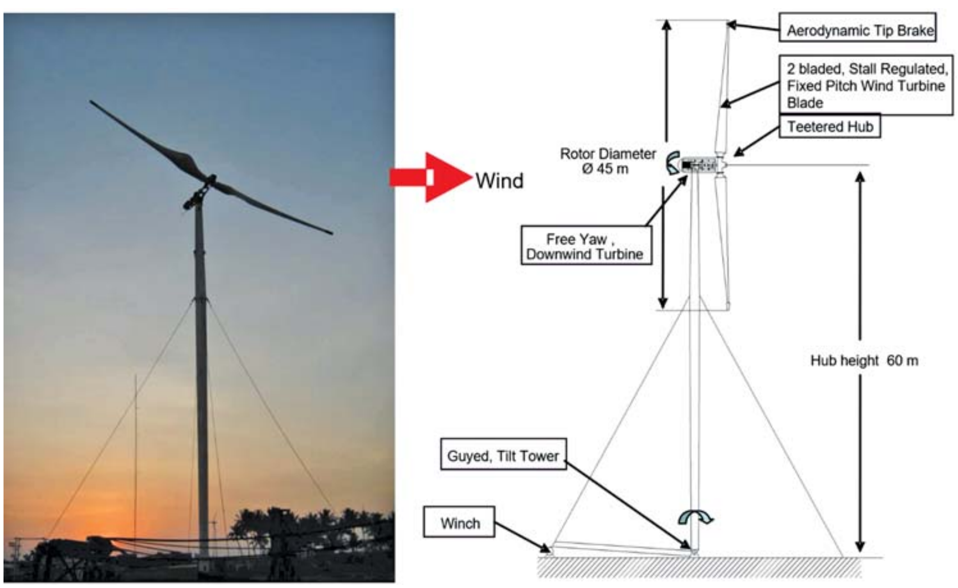


Fig. 19: Concept and actual 500 kW wind turbine developed by CSIR–NAL.

the private industry M/s SGC, Coimbatore in a Public-Private-Partnership (PPP) mode. A 500 kW wind turbine, that would optimally work in Indian low and dusty outdoor conditions, was developed indigenously. High-fidelity simulation tools like in-house Computational Fluid Dynamics (CFD) code Implicit Reynolds Averaged Navier Stokes (IMPRANS), commercial Finite Element Method (FEM) codes, and aero-elastic code Garrad Hassan (GH)-Bladed were used for detailed design. Composite blades were manufactured at CSIR–NAL and the metallic components were outsourced to local Micro, Small, and Medium Enterprises (MSMEs) in Tamil Nadu. Rigorous in-house testing of different components like non-destructive evaluation (NDE), multi-point deflection testing and balancing of the individual composite blades, rotor assembly static balancing, generator testing, high-speed shaft disk brake testing, pre-dispatch assembly of the drive train and the platform, destructive testing of the ferrule joints of the guy wires were carried out. Installation, commissioning, and field trials were carried out with local support of site engineers at Sangeeth Wind Farm, Kethanur (Fig.19)[25]. To capture the performance of the turbine, the full-scale 45 m dia. wind turbine was instrumented. Data acquisition was put in place through telemetry systems and National Instrument-based customized data acquisition systems. Field trials were conducted, and the performance of the system was verified and validated. Prominent features of the 500 kW system were employment of aerodynamic stall for regulating the power in high wind conditions, bioinspired CFRP tip brake, downwind configuration to avoid complex yaw sub-system, tilt down type guyed supported tower to ease maintenance and reduce the tower weight and an innovative and economical cruciform foundation to anchor the tower guy wires. Field trials endorsed the expected theoretical power curve.

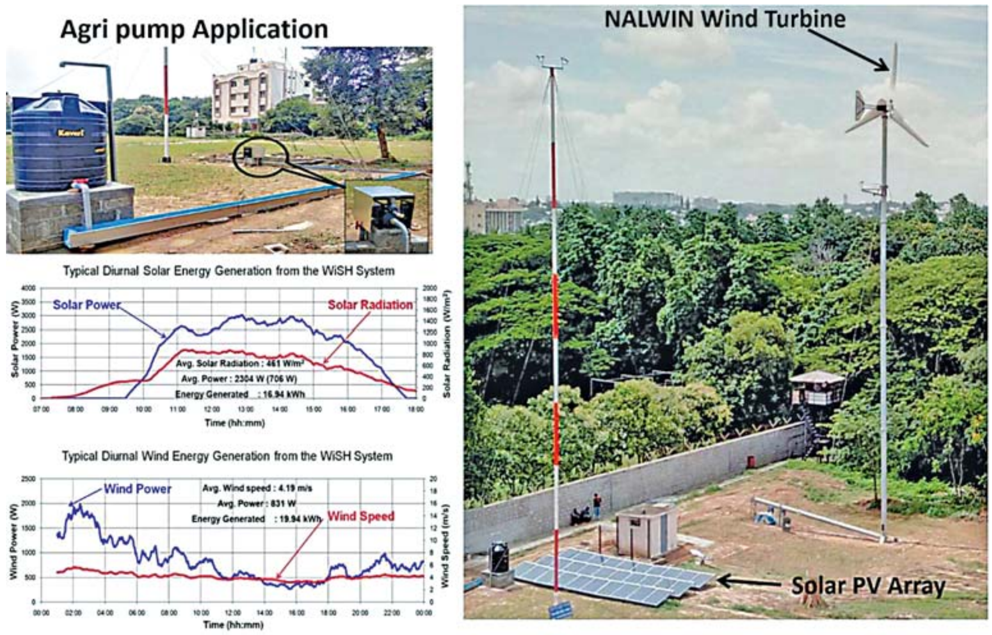


Fig. 21: 7.5 / 7.5 kW WiSH Technology Demonstrator at Kodihalli Campus, Bengaluru.

Fig. 20: 1/1 kW WiSH systems of CSIR–NAL installations across India.

CSIR–NAL's WiSH, its Transfer of Technology, and the DANIDA Program (Period from 2012 till present time)

It is a well-known fact that wind is intermittent in nature. Hence, for a sustainable green energy solution catering to the energy needs, it is imperative to hybridize wind with other renewable energy sources. Following this thought process, CSIR–NAL initiated a new research program on developing *Wi*nd – *S*olar *H*ybrid (WiSH) systems of different classes in 2012. The prototype was a 1/1 kW WiSH system, i.e., 1 kW wind turbine hybridization with 1 kW solar photovoltaic panels. It was designed, developed, and tested to gain experience in understanding the practical issues of hybridizing two different renewable energy sources and perfecting the architecture to optimize the energy mix. Later, the 1/1 kW WiSH system was offered as technological infrastructure to Science and Engineering institutions through M/s Aparna Renewable Energy Sources Pvt. Ltd., Bengaluru and as technology demonstrators at sister CSIR labs like Structural Engineering Research Centre (SERC), Chennai, Institute of Minerals and Materials Technology (IMMT), Bhubaneswar, Central Building Research Institute (CBRI), Roorkee, and Indian Institute of Petroleum (IIP), Dehradun (Fig. 20) [26,27].

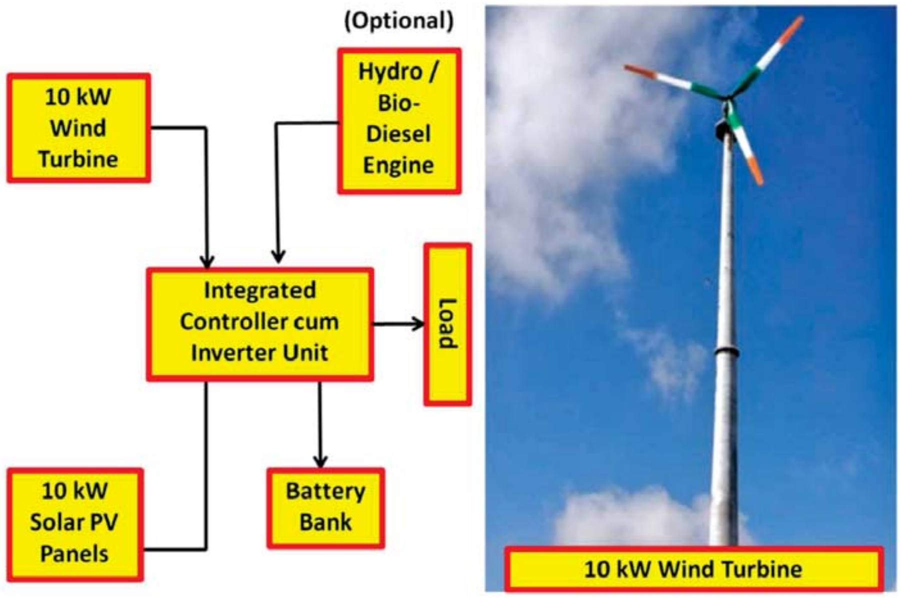


Fig. 22: 10/10 kW WiSH System architecture and 10 kW Technology Demonstrator.

With the experience gained in the development of a 1/1 kW WiSH system, CSIR–NAL embarked on developing a 7.5 kW wind + 7.5 kW solar WiSH system. This was a scaled-up technology demonstrator of the 1 / 1 kW WiSH system and targeted to cater to the off-grid energy demand of water pumping applications. The unit was designed, developed, and demonstrated at renewable energy farm, Kodihalli Campus, CSIR-NAL (Fig. 21)[26].

CSIR–NAL continued to research further and developed a 10 kW wind + 10 kW solar WiSH system that would cater to the community level energy needs of rural populace. Several additional features were added to the existing WiSH system architecture. These included multiple aerofoil cross-section shapes instead of a single airfoil

Fig. 23: ToT of CSIR–NAL's WiSH system.

along the blade span for enhancing the aerodynamic efficiency of rotor, usage of an alternator in place of a permanent magnet generator to address the issue of cogging torque and improve start-up and cut-in speed, active yaw system instead of conventional passive tail vane based system for enhanced overspeed protection, an integrated controller cum inverter unit with islanding and anti-islanding and capability to accommodate additional tertiary energy source and for efficient energy export in off-grid and on-grid mode (Fig. 22)[26].

MSMEs across India recognized the merits of the WiSH systems developed by CSIR–NAL. This resulted in the Transfer of Technology of the WiSH system to M/s Archimedes Green Energys Pvt. Ltd., Hyderabad in February 2020 (Fig.23)[27]. At present, CSIR–NAL is hand-holding the ToT partner for technology absorption and commercialization.

Apart from product development, CSIR–NAL made a mark in fundamental research of developing in-house and eco-friendly rain erosion coatings for wind turbine blades under a sponsored project from DANIDA entitled "Maintenance and Repair Strategy for Wind Energy Development." In this sponsored program, CSIR–NAL partnered with the Department of Wind Energy, Technical University of Denmark, Denmark, Clobotics Wind Services, Denmark, Indian Institute of Technology Delhi, National Institute of Wind Energy (NIWE), Chennai, WISH Energy Solutions, Pune, and WindCare India Pvt., Ltd., Chennai. Presently, dedicated team at Surface Engineering Divisions (SED), CSIR–NAL is developing eco-friendly and robust water-based polyurethane (WPU) reinforced ceramic oxides and cellulose coatings to safeguard the leading edges of wind turbine blades from solid particle and rain erosion[28–30]. It has been demonstrated that developed coatings show excellent solid particle erosion resistance performances compared to neat WPU and glass fibre reinforced polymer (GFRP) substrate.

Concluding Remarks

It is an accepted fact that India needs to harvest the untapped wind energy potential and reduce greenhouse gas (GHG) emissions, reduce carbon footprint, and combat the ill effects of climatic changes. The only key to achieving this target is to have indigenous expertise and "*Swadeshi*" technologies supported by the domestic supply chain eco-system. CSIR–NAL has been working since 1959 on developing technologies for harvesting wind energy based on its in-house knowledge base in aerospace science. The present article is an attempt to pen-portray CSIR–NAL's voyage to foster research and development of in-house technologies and products to harvest wind energy.

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